

Globally gridded satellite (GridSat) observations for climate studies

Kenneth R. Knapp¹, Steve Ansari¹, Caroline L. Bain², Mark A. Bourassa³, Michael J. Dickinson⁴, Chris Funk⁵, Chip N. Helms⁶, Christopher C. Hennon⁷, Christopher D. Holmes⁸, George J. Huffman⁹, James P. Kossin¹, Hai-Tien Lee¹⁰, Alexander Loew¹¹, Gudrun Magnusdottir¹²

¹ NOAA National Climatic Data Center, Asheville, North Carolina

² University of California at Irvine, Irvine, California now at Met Office, Exeter, Devon, UK

³ Florida State University, Tallahassee, Florida

⁴ Department of Earth and Atmospheric Sciences, The University at Albany/SUNY, Albany, New York, now at WeatherPredict Consulting, Wakefield, Rhode Island

⁵ USGS Center for Earth Resource Observations and Science, Santa Barbara, California

⁶ University of North Carolina Asheville, Asheville, North Carolina, now at Florida State University, Tallahassee, Florida

⁷ University of North Carolina Asheville, Asheville, North Carolina

⁸ Department of Earth and Planetary Science, Harvard University, Cambridge, Massachusetts

⁹ Science Systems and Applications, Inc. and NASA Goddard Space Flight Center, Greenbelt, Maryland

¹⁰ Cooperative Institute for Climate Studies (CICS), University of Maryland, College Park, Maryland

¹¹ Max-Planck-Institute for Meteorology, KlimaCampus, Hamburg, Germany

¹² University of California at Irvine, Irvine, California

To be submitted to the *Bulletin of the American Meteorological Society*

Capsule Summary: “Calibrated and mapped geostationary data provides historical satellite data to non-satellite experts for studies of weather and climate.”

Corresponding Author:

Kenneth R. Knapp

NOAA/National Climatic Data Center

151 Patton Ave.

Asheville, NC 28801

Ken.Knapp@noaa.gov

Phone: 828-271-4339

Fax: 828-271-4328

Abstract

Geostationary satellites have provided routine, high temporal resolution Earth observations since the 1970s. Despite the long period of record, use of these data in climate studies has been limited for numerous reasons, among them: there is no central archive of geostationary data for all international satellites, full temporal and spatial resolution data are voluminous, and diverse calibration and navigation formats encumber the uniform processing needed for multi-satellite climate studies. The International Satellite Cloud Climatology Project set the stage for overcoming these issues by archiving a subset of the full resolution geostationary data at ~10 km resolution at 3 hourly intervals since 1983. Recent efforts at NOAA's National Climatic Data Center to provide convenient access to these data include remapping the data to a standard map projection, recalibrating the data to optimize temporal homogeneity, extending the record of observations back to 1980, and reformatting the data for broad public distribution. The Gridded Satellite (GridSat) dataset includes observations from the visible, infrared window, and infrared water vapor channels. Data are stored in the netCDF format using standards that permit a wide variety of tools and libraries to quickly and easily process the data. A novel data layering approach, together with appropriate satellite and file metadata, allows users to access GridSat data at varying levels of complexity based on their needs. The result is a climate data record already in use by the meteorological community. Examples include reanalysis of tropical cyclones, studies of global precipitation, and detection and tracking of the intertropical convergence zone.

With the recent passing of the 50th anniversary of the first U.S. weather satellite, questions on how to best use historical satellite data come to the forefront of the discussion on climate observation. There are now over 30 years of globally sampled geostationary and polar satellite data, and while the visible and infrared imaging instruments on the satellites were not specifically designed for climate purposes, the record has great potential to be used for observational climate studies. With this in mind, NOAA recently embarked on an effort to derive Climate Data Records (CDRs) from environmental satellite data (National Research Council 2004), including geostationary satellites. At present, most CDRs derived from historical satellites are based on polar orbiting instruments, such as sea surface temperature data (Reynolds et al. 2002). Climatic use of geostationary data has been limited largely to satellite experts – e.g., the international community activities of the Global Energy and Water Experiment (GEWEX) such as the International Satellite Cloud Climatology Project (ISCCP) and the Global Precipitation Climatology Project (GPCP).

Numerous issues hinder use of the complete global geostationary data record by the climate research community. First, each country archives its own geostationary data. Thus, to obtain global data, one would access data from the U.S. (for the Geostationary Operational Environmental Satellites, GOES), Europe (for the Meteorological Satellites, Meteosat) and Japan (for the Geostationary Meteorological Satellites, GMS, and Meteorological Satellite, MTSAT). Second, the volume of full resolution data can be unwieldy for any study at climate time-scales. Third, the data format from each agency will be heterogeneous; furthermore, the data from any one agency will likely have multiple file formats. Assuming a user can overcome these hurdles, they must also calibrate (i.e., calculate radiances and brightness temperatures from the data) and

navigate (i.e., determine the latitude and longitude for each image pixel) the data from each of the satellites.

As mentioned, the ISCCP and GPCP projects are two of the few climate uses of geostationary data prior to 2000. This is due in part to the international collaboration that overcame the hindrances described above. In particular, the ISCCP stored a subset of satellite data at NCDC called ISCCP B1 that included data from each international meteorological satellite. However, necessary information about the data such as file format, navigation algorithms, etc. were not archived. This caused the ISCCP B1 archive to be mostly unusable until a rescue effort rectified these issues (Knapp et al. 2007) and provided access to the data for 1983 to present. In addition, further efforts (Knapp 2008a) have expanded the period of record back to 1980.

The ISCCP B1 data have since been processed into Gridded Satellite (GridSat) data, a format that is easily accessed and processed by the climate research community at large. This paper describes the construction of the dataset – describing some of the aspects of how the data are provided to facilitate user access – and highlights some of the applications of GridSat. Along the way, the reader is not only encouraged to consider GridSat as a tool for better understanding the Earth’s climate, but also as an example of how other observational data could be provided to a broad user community.

GridSat overview

GridSat data are derived from the ISCCP B1 data, which are detailed by Knapp (2008a). In short, the data are similar to the Hurricane Satellite (HURSAT) data (Knapp and Kossin 2007), but at a global scale. As a result, GridSat’s spatial, temporal, and spectral features that are

described below are similar to HURSAT. The characteristics of the GridSat data are provided in Table 1.

The NOAA Climate Prediction Center (CPC) produces a globally-merged IR product called the CPC-4km product (Janowiak et al. 2001). This product is created in real time and used to monitor global precipitation. Because of the similarity between GridSat and CPC-4km, the details of CPC-4km are provided alongside GridSat in Table 1. The primary difference between the two datasets is that the CPC-4km product is geared toward real-time weather application while GridSat targets long term global processing. For instance, both datasets attempt to reduce inter-satellite differences by intersatellite normalization, however, GridSat also performs temporal normalization via calibration against HIRS during the GridSat period of record. Thus, the data are complementary.

GridSat data are provided in an equal angle map projection (also called equirectangular or plate carrée), which facilitates the mapping and subsetting of the data. Since the ISCCP B1 native resolution is approximately 8km, the resolution of the equal area grid is 0.07° latitude ($\sim 8\text{km}$ at the Equator). The data span the globe in longitude and range from 70°S to 70°N . The spatial and temporal coverage of the satellites contributing to ISCCP B1 is provided in Figure 1 – the so-called “geostationary quilt”. While the first year of GridSat data (1980) is mostly composed of satellites in the GOES-East and West positions (Figure 1b), a four-satellite constellation is representative of the period from 1982 through 1998. (e.g., Figure 1b). Failures of satellites often caused a three-satellite configuration but nearly global coverage is still possible (Figure 1d), though at large view zenith angles. Finally, the Indian Ocean gap was filled in 1998, completing the global coverage (Figure 1e). In recent years, coverage has increased with the provision of the Chinese Fen Yung (FY) geostationary satellites and the loan of GOES satellites

for a South American coverage at 60° west. The satellite intercalibration by Knapp (2008b) effectively stitches each quilt piece together, allowing for a consistent global dataset.

GridSat Channels

In spite of the diversity of satellites and nations providing data, the ISCCP B1 can provide a uniform set of observations for the infrared window (IR) and visible channels – at 11 and 0.6 μm , respectively – during the period of record of ISCCP B1 data. Since 1998, the infrared water vapor channel (WVP) near 6.7 microns is also available on a global basis.

The IR channel is a window channel (i.e., a region with little atmospheric absorption) that senses the Earth's surface under clear sky conditions, cloud top temperatures of thick clouds, and a combination of cloud and surface for optically thin clouds. Many applications of this channel are discussed below.

The visible channel is also a window channel that provides information on clouds and the surface. This channel also has the potential to provide information on Earth radiation budget variables such as aerosols (Knapp 2002) and surface albedo (Loew and Govaerts 2010).

The WVP channels are generally centered near 6.7 μm , which is in a water vapor absorption band making it sensitive to humidity in the upper troposphere. This can provide information on circulation patterns. However, this channel has limited global coverage, beginning only in 1998.

Inter-satellite calibration

The data in GridSat use the intercalibration provided by ISCCP calibration efforts (Desormeaux et al. 1993) for the IR and visible channels. The IR channel has also undergone a second intercalibration using the High resolution Infrared Radiation Sounder (HIRS) as a

reference, which detected and corrected bias in the ISCCP calibration at cold temperatures after 2001 (Knapp 2008b). The WVP channel calibration can be tied to a HIRS upper level water vapor channel (channel 12) but is complicated by the switch in central wavelength between HIRS/2 to HIRS/3 (from 6.7 to 6.5 μm) and is still being tested.

Data are calibrated and stored in files as brightness temperature for longwave channels (IR & WVP) and reflectance for the visible channel. The IR data are calibrated following Knapp (2008b), view zenith corrected following Joyce et al. (2001) and parallax-corrected following Janowiak et al. (2001).

GridSat Production

For each 3-hour time slot, the IR, WVP and visible channels on each satellite are mapped to an equal-angle grid using nearest-neighbor sampling. Areas of satellite overlap are retained by storing data in layers (see Figure 2) using the following technique. For each channel, the primary layer retains observations with the nadir-most (i.e., the lowest) view zenith angle, while a secondary layer holds the regions dropped from the first layer. Similarly, a tertiary layer is retained for the third-best view zenith angles (that are dropped from the secondary layer). The extra layers are provided for future intercomparisons and intercalibrations (i.e., developing algorithms for various zenith angles). Furthermore, a satellite can be reconstructed by combining its contributions to each layer (e.g., by taking all the orange portions from each row of Figure 2, one can reconstruct the GOES-11 satellite).

In addition to the channel data, satellite identification is stored per pixel with corresponding satellite information: satellite latitude, longitude and radius. So while pixel-level satellite view zenith and azimuth angles are not stored, they can be calculated using the Earth

151 location and the stored satellite position (Soler and Eisemann 1994). Furthermore, calibration
152 information for each channel is provided such that original ISCCP B1 satellite counts can be
153 backed out

154 Data are stored using netCDF (Rew and Davis 1990) and CF conventions that facilitate
155 usage with other software (see sidebar). Channel primary layers (nadir-most observation) are
156 written as 2-dimensional (2D) grids in the netCDF file, which facilitates processing of multiple
157 files (e.g., aggregation of multiple times, etc.). Subsequent layers are written as either 2D grids
158 or staggered arrays, which are 1-dimensional arrays that only record data when they exist.
159 Staggered arrays are more efficient when storing maps where data are mostly missing, as is often
160 the case for the tertiary layer.

161 **Sidebar: netCDF and CF compliance: Simplifying data access** 162 **and processing**

163 Recent advances in data services allow access and dissemination of data to a broad user
164 community such that data servicing is now more than just putting files on an FTP server. Data
165 servers provide numerous capabilities to users, for example allowing them to download only the
166 data of interest, which saves download bandwidth and research time. Some of the capabilities are
167 summarized below along with a real example of how data processing can be simplified with
168 available tools.

169 The netCDF data format is supported by Unidata and has libraries that allow access to the
170 data from dozens of programming languages. The recent version update of netCDF also allows
171 for data compression that results in smaller storage and bandwidth requirements. The GridSat
172 data are stored in netCDF using the Climate and Forecasting (CF) convention. By complying
173 with CF, GridSat data are stored in a manner that other tools recognize, for example, providing

the coordinates of the data variables. In addition, tools such as the netCDF library and netCDF operators (NCO) (Zender 2008) are capable of reading files across the Internet without previously downloading the data.

GridSat data are served using the THREDDS data server (TDS) developed by Unidata, which allows users various options for downloading data. The TDS OPeNDAP access allows an OPeNDAP client (such as the NetCDF library, NCO, IDV and more) to remotely subset and download only the desired data slice or pixel. This provides efficient access to very large files or aggregations (i.e., virtual groups of files) without the user needing to download the entire file. The TDS Web Map Service access allows applications such as GIS, Google Earth, or online mapping to directly request rendered images (gif, png, jpeg) from the data server. These images already have a color table applied and can be produced in a variety of predefined projections. The TDS NetCDF Subset Service provides a web-based 'slice-and-dice' service for users. Users may extract a spatial and temporal subset of the data and save the results as CF-compliant NetCDF, XML or comma-separated variable (CSV) text files. Therefore, a variety of user access methods exist that provide interoperability with many existing software tools. Each method can be invoked by a single URL, enabling easy automation and scripting.

Numerous tools have been created to simplify the processing of CF compliant data. More than just data visualization, tools like NCO provide command line capabilities to perform averages, concatenations, and more. For instance, sample code is provided in Figure SB1 that processes one month of GridSat IR data, creating diurnally averaged IR brightness temperatures over the Sahara Desert for July 2002. Similar code was used to process the global diurnal trend maps in the outgoing longwave radiation section. The calls to NCO (*ncra* and *ncrcat*) provide a simple means to average IR brightness temperatures (via the *-v* flag) for a specific region (via

the `-d` flag) and concatenate the files together. The alternative would be writing hundreds of lines of source code (e.g., C or FORTRAN) to read in the data, calculate the diurnal average, define the output file and write the data. Instead, the seven line shell script accomplishes the same task. The resulting data can then be displayed easily with GrADS (using only 4 commands), for example, to show the mean temperature change from 3 to 15 UTC over the Sahara Desert (Figure SB2).

In summary, it is clear that processing gridded netCDF data – such as GridSat – is simplified by CF compliance and the many tools available for serving and processing CF-compliant netCDF data.

Dataset applications for infrared window data

Here we present a selection of real-world climatological studies that depend upon GridSat. The aim is to demonstrate the diverse nature of satellite data usage, and emphasize why historic satellite data is of importance to numerous scientific communities. Many of these users are non-expert satellite users who would be otherwise unable to process uncalibrated and unmapped satellite data in a timely manner. The applications of GridSat described below are limited to the IR channel data, which has received the more extensive inter-satellite calibration. The IR data have been applied to tropical cyclones, the Intertropical Convergence Zone (ITCZ), global and regional precipitation monitoring and outgoing longwave radiation.

Tropical cyclones

Given the current questions regarding tropical cyclone variability in a warming climate and the challenges posed by the large uncertainties and heterogeneities in the historical tropical records, one very natural application of GridSat is toward the homogenization of these records.

GridSat has been used to detect tropical cyclones, estimate their intensity and wind structure, and follow them through their lifetimes from genesis to their demise or transition to extra-tropical storms.

Tropical disturbances and cyclogenesis

Tropical disturbances are early precursors to tropical cyclones. Traditionally, disturbances have been tracked and evaluated according to the Dvorak technique (Dvorak 1975, 1984), which estimates intensity based on the shape and evolution of cloud cover. This technique works best for systems nearing tropical cyclone stage; it is much less effective for weaker systems. The GridSat data set is useful for a newer approach that also utilizes surface vector wind information. Scatterometer wind vectors can be used to estimate areal averaged surface vorticity (Bourassa and McBeth-Ford 2010; Sharp et al. 2002). The surface conditions used to identify tropical disturbances are a threshold area-average vorticity of $5.0 \times 10^{-5} \text{ s}^{-1}$, combined with a minimum wind speed of 6.3 m s^{-1} within the averaging area. Furthermore, the first two conditions must be met often enough in a 50 km radius area (Bourassa and McBeth-Ford 2010; Gierach et al. 2007). Coverage from a single scatterometer is insufficient to confidently track tropical disturbances. Therefore, Gierach et al. (2007) combined cloud-top IR observations with the surface vorticity to identify likely tropical disturbances. The cloud cover could be tracked to provide continuity between scatterometer observations. This technique proved to be quite effective for the North Atlantic basin (Gierach et al. 2007) and is now being investigated for other hurricane basins.

Given the limited period of record of scatterometer data, another approach has been developed that uses only the IR data to detect potential tropical disturbances. One requirement

for tropical cyclogenesis is the existence of a large area of intense and persistent thunderstorms, called a cloud cluster. During a typical hurricane season in the Atlantic, there are usually more than 100 cloud clusters that form and move across the basin. Cloud clusters are associated with easterly waves, stalled mid-latitude fronts, and large areas of atmospheric instability. Lee (1989) defined a cloud cluster as: being independent of other systems, having a diameter of at least 4° latitude (not elongated) and persisting for at least 24 hours. Owing to their critical importance in the tropical cyclogenesis process, several recent studies (e.g., Hennon and Hobgood 2003) have manually compiled a large dataset of cloud clusters for study, a time-consuming task that involves examining hundreds or thousands of basin-wide IR imagery individually.

In contrast, Hennon et al. (2011) objectively identified cloud clusters in GridSat data by testing the IR brightness temperature (Tb) data. The process uses a threshold to detect deep convection, and then applies spatial and temporal analysis to determine whether a region meets the definition of a cloud cluster. Figure 3 shows the frequency (number of clusters per year) of objectively identified cloud cluster tracks for first decade of global coverage (1998-2007). The highest densities are found in the Intertropical and South Pacific convergence zones, North Indian Ocean, and off the west coast of Africa. These areas are consistent with observed areas of cloud cluster activity and tropical cyclogenesis. This cloud cluster dataset spans nearly 30 years and could be applied to several areas of research, including: intraseasonal and interannual studies, impacts of a warming world on cloud cluster activity, and case studies for use in tropical cyclogenesis research (e.g., using Knapp et al. 2010).

Understanding cyclone intensity and structure

Tropical cyclones are monitored and forecasted by a number of forecast agencies worldwide. Most forecast agencies provide estimates of the location and intensity of tropical cyclones in their areas of responsibility, but processes and data have improved over time. This makes the historical record of TC intensity heterogeneous by construction. Conversely, studies of the changes to tropical cyclone intensity require data with no temporal heterogeneities. HURSAT data, in essence, derive from GridSat collocated with tropical cyclones in the IBTrACS data record (Knapp and Kossin 2007), see Figure 4. Kossin et al. (2007a) used HURSAT to objectively estimate TC intensity by exploiting well-known relationships between intensity and the satellite presentation of the storms. Additionally, the wind structure inside the tropical cyclone can be derived from HURSAT (Kossin et al. 2007b), providing information about the extent from the storm center that storm force winds reach. So in addition to the climatic perspective, GridSat data (via HURSAT) also provide an understanding of tropical cyclone conditions throughout their lifetime.

Tropical cyclone transition to extratropical systems

Tropical cyclones moving out of the tropics poleward to the middle latitudes can undergo significant structural and intensity modifications due to changes in the surrounding large-scale environment. In general, these tropical systems are weakening as they accelerate poleward over colder sea surface temperatures (or move over land) and into an increasingly baroclinic environment. Broadly speaking, extratropical transition (ET) is the conversion of a symmetric, vertically stacked, warm core tropical cyclone with maximum intensity in the lower troposphere into an asymmetric, cold core and tilted extratropical cyclone with maximum intensity in the

upper troposphere. The evolution of the ET is sensitive to the interaction of the decaying tropical cyclone with the mid-latitude circulation; see Jones et al. (2003) for a thorough review. During ET, the cloud and precipitation shield expands ahead and to the left of the tropical cyclone center, in response to the synoptic forcing associated with the approaching mid-latitude trough. ET events can be tremendous rain makers as the large area of synoptically driven ascent can act on abundant tropical moisture. Numerous studies show that ET is common in the Atlantic (Hart and Evans 2001), western Pacific (Klein et al. 2000), and Australian (Foley and Hanstrum 1994; Sinclair 2002) basins, but not the eastern Pacific basin.

GridSat, via the HURSAT dataset, is being used to document in detail the remarkable events of late August 1992. During this period, the first ever documented ET in the Eastern Pacific Ocean: Hurricane Lester over the southwestern United States. At the same time, Hurricane Andrew devastated south Florida and made a second landfall along the central Louisiana coast. Andrew was then steered poleward ahead of the same baroclinic system responsible for the ET of Hurricane Lester just days prior. Finally, the upscale impact of Lester and Andrew on the synoptic-scale flow led to the downstream development and the generation of a “vorticity seed” in the western Atlantic. Despite favorable sea-surface temperatures and low vertical wind shear, no tropical system developed. All of which are directly related to each other.

ITCZ Detection

GridSat’s coverage in the tropics is ideal for the study of larger scale weather features that may exceed the vision of a single geostationary satellite. The ITCZ is one such feature. It occurs as a narrow band spanning the tropics where the trade winds meet, and is visible as a region of increased convective activity. This highly dynamic and variable weather feature has

been studied in observations mostly in a time-averaged sense. The transient nature of the ITCZ makes accurate detection for process studies challenging. Previous studies have used analysis products (e.g., Magnusdottir and Wang 2008), have manually labeled satellite frames and therefore only use a few years of data (e.g., Wang and Magnusdottir 2006), or have thresholded brightness temperature to identify the ITCZ (Waliser and Gautier 1993). The latter has the disadvantage of including convection not associated with the ITCZ. Bain et. al. (2011b) developed a statistical model for ITCZ detection (along with uncertainty measures) and applied it to GridSat for its entire period of record, providing a long record of ITCZ variability in the east Pacific.

The statistical model of ITCZ detection objectively identifies the envelope of convection in a probabilistic framework that is described in detail by Bain et. al. (2011b). The method requires that the satellite dataset be reliably calibrated over long periods and available at high temporal resolution, although the model can easily accommodate occasional data gaps. It is also important that there are no noticeable discontinuities when satellites are changed. The GridSat dataset is ideal for this approach. Figure 5 demonstrates the objectively tracked ITCZ in the east Pacific. The black line represents the envelope of convection that the statistical model has determined is part of the ITCZ. Note that some isolated convection is not included as part of the ITCZ since it is determined not to be related to the larger scale feature.

Using this technique, a database was created identifying the ITCZ in the east Pacific (90 - 180W, 0 - 30N) every 3 hours from 1980 to 2008. The database has been used to construct detailed analysis of the climatology of the ITCZ as well as seasonal and inter-annual variability (Bain et al. 2011b). The additional advantage of the high temporal sampling has also allowed in-depth studies into the diurnal cycle of the ITCZ in Bain et. al. (2011a), where the size of the

328 ITCZ as well as the character of clouds within in it were found to vary according to time of day.
329 The ability to use the same dataset for both short timescales and long timescales lends strength to
330 investigations of the ITCZ and is therefore particularly useful for relating climatological and
331 dynamical aspects of the feature.

332 **Precipitation**

333 The detection of precipitation is not wholly unrelated to the above applications, as both
334 tropical cyclones and the ITCZ can cause copious amounts of precipitation. The following details
335 the study of precipitation using GridSat in global and regional studies.

336 *Global precipitation climatologies*

337 Compared to microwave and infrared sensors, which are typically used for the generation
338 of long-term precipitation climatologies (e.g., Adler et al. 2003; Xie and Arkin 1997), GridSat
339 provides complementary information at high temporal and spatial resolution in three different
340 channels. The high spatial resolution of GridSat can help to better identify cloud systems capable
341 of producing rain while the high temporal resolution allows for tracking the development and
342 movement of medium- and large-scale cloud systems. The data from the IR channel can be used
343 to better identify convective cells and therefore resolve precipitating systems with a scale smaller
344 than the footprint of a microwave sensor [similar to the approach of Joyce et al. (2004)]. Merging
345 the multi-spectral and high resolution GridSat data with data from sensors on polar orbiting
346 satellites might be a fruitful pursuit, which could allow for temporal interpolation between
347 subsequent overpasses of a microwave sensor that only provide a few observations per day at a
348 global scale.

Erroneous discrimination of optically thin and thick clouds can have a significant effect on uncertainties in precipitation retrieval (Ba and Gruber 2001). Non-precipitating cirrus clouds mistakenly interpreted as thick precipitating clouds contribute to overestimation of rain rate. Differencing between GridSat IR and WVP data allows one to discriminate between optically thin clouds and thick clouds possibly overlaid by cold ice clouds (Turk and Miller 2005). While the WVP channel is primarily sensitive to the water vapor in the upper troposphere, the IR channel is sensitive to the cloud top temperatures. Optically thick clouds reaching the upper troposphere would produce low values in both channels, so the difference between them would be very small. In the opposite case, when optically thin ice clouds overlay ground surface or lower clouds with relatively warm tops, brightness temperature in the IR would be significantly less than the WVP. The same technique could be applied to discriminate cold cloud tops from ground surface covered by snow or ice. Thus, GridSat data will likely have a significant impact on global precipitation climatologies.

Mercury wet deposition: Polluted rain

At regional scales, Holmes (2008, 2010) applied GridSat data to the study of societal impacts of precipitation in the eastern United States. Wet deposition is a major source of mercury to ecosystems, which can then be converted to methylmercury that may bioaccumulate to harmful levels in fish, birds and humans (Lindberg et al. 2007; Mergler et al. 2007; Scheuhammer et al. 2007). Many US water bodies exceed the mercury concentrations allowed by the Clean Water Act, motivating efforts to understand and reduce mercury exposure through precipitation.

Mercury deposition in the southeast US is nearly double that in the northeast despite lower anthropogenic emissions in the region, seen in Figure 6a (Environmental Protection Agency 2008; Mercury Deposition Network 2006). Peak seasonal deposition occurs in summer when convective storms are common. This led Guentzel et al. (2001) and Selin and Jacob (2008) to hypothesize a causal link between high-altitude wet scavenging in deep convection and the elevated deposition. Holmes (2008, 2010) tested this hypothesis by correlating IR cloud temperatures from GridSat with mercury deposition measured by the EPA Mercury Deposition Network (MDN). Figure 6a shows data from 8 MDN sites in the southeast during June-September of 2001-2006. Precipitation samples accumulate over 1 week and the associated cloud temperatures are calculated as the average over the collection period of daily minimum temperatures observed within 20 km of the collection site. Deposition clearly increases with colder temperatures (Figure 6b), but this is partially due to large precipitation depths associated with tall, cold clouds. Figure 6c shows that even for equivalent rainfall depths, mercury deposition is about 2 times greater in the samples with the coldest average clouds ($T_b < 240$ K) compared with the warmest ones ($T_b > 260$ K). Ongoing work addresses the dynamical implications of these results.

Precipitation and temperature monitoring in data sparse regions

Another societal implication of precipitation is the availability of food production in regions with little irrigation infrastructure. Adverse trends in rainfall and temperature can disrupt agriculture and pastoral livelihoods that are already being impacted by local and global population growth, expanding economies, and increased demand for limited environmental resources. Therefore, the US Agency for International Development Famine Early Warning

Systems Network (FEWS NET) has supported the creation and analysis of rainfall and temperature climatologies in food insecure regions. This work has identified significant rainfall declines throughout Eastern Africa with the most dramatic declines in Ethiopia and Kenya (Funk and Brown 2009; Funk et al. 2008; Funk et al. 2005). If rainfall declines or temperature increases have exacerbated food insecurity across the Sahel or Eastern Africa, exactly where have these changes occurred? Our response, along with our ability to guide adaptation efforts, has been limited by sparse *in situ* data. FEWS NET has begun working extensively with the GridSat data, which may help us make much finer resolution maps of rainfall and air temperatures over a thirty-year period.

We provide here an example based on July-September rainfall and air temperature for eastern Africa and the Sahel. The first analysis step involves the separation of cold and warm IR values for each observation time. For each four-month season, the ~120 3-hourly time-slices are sorted, and the 10th (cold) and 90th (warm) percentiles retained. The 10th and 90th percentile fields are then averaged across the eight 3-hour periods. The result is a field of the mean 10th and 90th percentile values for each July-September, from 1980 to 2008. The exciting thing about these fields is that they effectively capture spatial variations in both temperature and rainfall. The 10th percentile fields correspond with the height of cold clouds, and effectively distinguish areas receiving heavy convective precipitation from those without. Conversely, the 90th percentile fields typically capture near-surface emissions that are related to land temperature.

Next, GridSat fields were averaged over two ten-year time periods: 1999-2008 and 1984-1993. These were then correlated with averages of *in situ* temperature and station data for the same periods. (where explained variances exceeded 70% for both parameters). We then use a moving window regression model to build a localized equation translating each IR value into a

10 km monthly mean temperature or precipitation. The mean 1999-2008 July-September temperature field is in the top-left of Figure 7. High mountainous areas in Kenya, Ethiopia and near the border of Cameroon and Nigeria are cool, while the sands of the Sahara and the Afar region of Ethiopia are very warm. Interactions between these mountains and the larger scale circulation bring heavy rains to western Ethiopia, and the inter-tropical front stretches across the Sahel (top-right). The region is beset with very strong environmental gradients that shift over time. These variations can be mapped by looking at decadal differences (here the difference between the 1984-1993 and 1999-2008 averages). Such differences may relate to climate change or may be simply due to inherent climate variability. In either case, decadal fluctuations can impact food security, hydrological resources, and environmental sustainability. The GridSat data help us capture shifts in these gradients, building a high resolution picture of change.

Looking at the temperature changes (Figure 7, bottom left), a substantial warming signal is apparent; temperatures appear to increase everywhere but some regions more than others. This signal also appears in the station data, with simple averages taken across all the in situ observations exhibiting a slope of 0.05 °C per year ($r^2=0.44$) with other months exhibiting similar trends. Spatially, however, the strongest warming ($>1^\circ\text{C}$ since 1984-1993) appears across a coherent area stretching from Western Kenya and Ethiopia across the Zaire basin. July-September rainfall, on the other hand, exhibits increases across northern Ethiopia and most of the Sahel. Decreases are found across eastern Ethiopia, most of Kenya and Uganda, and the Zaire basin.

The spatial detail of these maps should help us understand and adapt to decadal climate variations. From a food security perspective, three patterns emerge: i) a dangerous warming trend across all the Sahel and eastern Africa, ii) combined warming and drying over the last ten

years across southwestern Ethiopia and southern Sudan, and iii) a smaller reduction in rainfall near the border of Mali and Senegal . While the GridSat-enhanced analyses are still evolving, it seems likely that these data will substantially improve our ability to track rainfall and temperature changes, enhancing our ability to adapt in a changing world.

Outgoing Longwave Radiation

The Earth radiation budget describes the distribution of radiative energy in the Earth-atmosphere system. The observations of Earth radiation budget parameters at the top of the atmosphere have been performed from both operational and experimental satellites since the 1970s. The long and continuous time series of Earth radiation budget parameters, e.g., the outgoing longwave radiation (OLR), is valuable for climate change studies and monitoring. The polar orbiters provide fairly uniform spatial and angular sampling from a given instrument, but with relatively poor temporal sampling resolution. Geostationary satellite observations provide information on the diurnal variation that is essential for deriving such time series accurately.

The HIRS OLR climate data record was generated with a set of climatological OLR diurnal models (Lee et al. 2007) that help to reduce the monthly OLR errors resulting from the orbital drift of polar-orbiting satellites. Although these models are self-consistent with the HIRS OLR retrievals, for error budgeting purposes, we would like to assess whether these diurnal models were truly representative and how significant the inter-annual variations can be. Figure 8 shows the comparison of the HIRS climatological OLR diurnal models for August 2002 with those derived from the GridSat IR data. Some disagreements are apparent for certain regions/climate types Nevertheless, for the majority, they seem to share a high degree of similarity, both in shape and in phase. These results provide us confidence in the quality and

guidance for future improvement of the OLR climate data record production. Similar comparisons are necessary for other seasons and years.

A hybrid OLR product can then be generated using HIRS observations and GridSat following Leet et al. (2004), similar in design to that used for the Cloud and the Earth Radiant Energy System (CERES; Young et al. 1998). Such a combination would take advantage of both the accuracy of the HIRS OLR retrieval and the precise diurnal variation signal in geostationary observations. This product will improve the temporal integral accuracy for the HIRS climate data record and possibly allow product generation at a temporal resolution finer than monthly, e.g., daily or pentad, which would benefit some dynamical diagnostic and precipitation estimation applications.

Future Work

Future applications using visible and water vapor channels

The bulk of the applications so far have focused on the IR channel, however many areas of study exist for the global inter-calibrated visible and WVP channels. The visible channel is sensitive to clouds and in some regions aerosols as well. Aerosols have a significant role in our daily lives by affecting human health and in our understanding of the Earth's radiation budget via the uncertainty in how much solar radiation they reflect to space versus absorb (in addition to how they affect cloud optical properties and lifetime). Knapp (2002) defined a means to detect the aerosol signal in satellite observations. When this technique is applied to visible GridSat data, many ground sites – Aerosol Robotic Network sites (Holben et al. 1998) – show a strong aerosol signal that implies (given a good cloud algorithm) aerosols can be retrieved from GridSat.

GridSat data also have the potential to help accurately determine shortwave and longwave radiation fluxes at the regional to global scale. The Earth's surface albedo is a key terrestrial variable in these flux calculations. While surface albedo data are available from the MODIS sensor since 2000 (Schaaf et al. 2002), long term surface albedo data products that cover multiple decades previously could only rely on operational weather satellites that were not designed for climate monitoring. The general potential to derive global maps of surface albedo from mosaics of geostationary observations has been shown by Govaerts et al. (2008) and the GridSat data might be used for the retrieval of global fields of surface albedo in this way. However a recent study (Loew and Govaerts 2010) has shown that uncertainties in the characterization of the spectral response function of the older generation of geostationary satellites might result in systematic biases and trends in multi-decadal surface albedo data products. An appropriate assessment of the uncertainties of each sensor's spectral characteristics and their impact on surface albedo estimates is therefore inevitable for the generation of essential climate records of surface albedo and surface radiation budget from GridSat data.

The WVP channel provides information on energetics of the upper troposphere. The channel is sensitive to a broad region of upper tropospheric humidity that can provide information on the distribution and transport of water vapor in the troposphere (Soden and Bretherton 1993; Tian et al. 2004). This channel also has the potential to provide information on water vapor entering the stratosphere (Schmetz et al. 1997) via overshooting convective clouds. In such cases, the WVP channel can be warmer than the IR channel for convection that penetrates the tropopause. GridSat data – in providing global coverage for both channels – has the potential to help monitor the transport of water vapor.

Dataset improvements

Given the widespread use of the GridSat dataset, efforts are underway to further improve the dataset. The ISCCP project is revamping software processing to produce higher resolution cloud products based on ISCCP B1 data. As part of this work, the pixel level cloud mask will be incorporated into GridSat, providing information on the presence of clouds in the GridSat data.

A new version of the GPCP datasets is now in development, with the GridSat data as one key upgrade. Using GridSat, spatial resolutions of GPCP will likely increase: the monthly GPCP product from 2.5° lat. to 0.5° and the daily will shift from 1° to 0.25°. In addition, the daily dataset eventually could be pushed from its current start of October 1996, perhaps to the start of Special Sensor Microwave Imager data in July 1987. For both datasets, the current latitude bounds for GPCP geostationary IR data of 40°N-40°S will be relaxed to the entire useful range of simple IR-based estimates, around latitude 50°- in the summer hemisphere.

Furthermore, the use of GridSat data by non-satellite experts suggests that a similar remapping would benefit other satellite data. For example, instruments on polar orbiting satellites could be remapped in a similar way as GridSat. This would likely make data – like that from AVHRR, HIRS and other instruments – more widely available to a broad base of users.

Lastly, the observations that comprise the GridSat data are being revised. The visible and WVP radiances will soon be intercalibrated (the latter is hindered by a change in HIRS water vapor central wavelength). The IR satellite view zenith angle correction should be improved as well. The current algorithm (Joyce et al. 2001) was developed for satellites in use in 2000 (GOES-8,10, GMS-5, Meteosat-5,7) however, the corrections are likely satellite dependent (particularly the older satellites that had more water vapor contamination in the infrared window

channels). An updated satellite zenith angle correction that is satellite dependent would decrease the remnant seams still apparent in GridSat IR data.

Summary

Geostationary satellites have now been providing weather data for 50 years. Much of these data have been neglected by climate observation studies due to difficulties with calibration and data processing over such a long period. Collection and data ownership rights were spread out across several international agencies. The ISCCP project is overcoming these barriers and this paper has presented details on the most up-to-date and easily accessible global satellite record: GridSat.

This new record provides equal-angle gridded uniform observations of brightness temperatures every 3 hours from 1980 to the present. We have demonstrated the multiple and diverse uses of the data – from predicting drought and food security in Africa to the detailed and historical tracking of hurricanes. This only touches on some of the potential uses of GridSat. Accurate records of global atmospheric fields are essential for future research on climate change as well as the understanding of the planet's meteorology.

By reconstructing past satellite data and combining them with current satellite observations, a seamless data record has been obtained for the study of the Earth's atmospheric state. In addition, GridSat has given a wide range of users very easy access to this new data record. Development of GridSat will continue, focusing on improving the current data files and supporting more applications.

Acknowledgements

K. Knapp acknowledges the significant contribution of George Huffman in the design of the GridSat dataset. Many were integral in the initial rescue of the ISCCP B1 data, including Bill Rossow, John Bates, Garrett Campbell and many at the agencies that provided the B1 data: JMA, EUMETSAT and NOAA. A. Loew acknowledges the support of the Cluster of Excellence 'CliSAP' (EXC177), University of Hamburg. Any use of trade, product, or firm names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

References

- Adler, R. F., and Coauthors, 2003: The Version-2 Global Precipitation Climatology Project (GPCP) Monthly Precipitation Analysis (1979-Present). *Journal of Hydrometeorology*, **4**, 1147-1167.
- Ba, M. B., and A. Gruber, 2001: GOES Multispectral Rainfall Algorithm (GMSRA). *Journal of Applied Meteorology*, **40**, 1500-1514.
- Bain, C. L., G. Magnusdottir, P. Smyth, and H. Stern, 2011a: The diurnal cycle of the ITCZ in the east Pacific. *Journal of Geophysical Research*, **In preparation**.
- Bain, C. L., J. De Paz, J. Kramer, G. Magnusdottir, P. Smyth, H. Stern, and C.-C. Wang, 2011b: Detection of the ITCZ in the east Pacific using Markov random fields on instantaneous satellite data. *Journal of Climate*, **Submitted**.
- Bourassa, M. A., and K. McBeth-Ford, 2010: Uncertainty in Scatterometer-Derived Vorticity. *Journal of Atmospheric and Oceanic Technology*, **27**, 594-603.
- Desormeaux, Y., W. B. Rossow, C. L. Brest, and G. G. Campbell, 1993: Normalization and Calibration of Geostationary Satellite Radiances for the International Satellite Cloud Climatology Project. *Journal of Atmospheric and Oceanic Technology*, **10**, 304-325.

568 Dvorak, V. F., 1975: Tropical Cyclone Intensity Analysis and Forecasting from Satellite
 569 Imagery. *Monthly Weather Review*, **103**, 420-430.
 570 ———, 1984: *Tropical cyclone intensity analysis using satellite data*. National Oceanic and
 571 Atmospheric Administration, National Environmental Satellite, Data, and Information
 572 Service, 47 pp.
 573 Environmental Protection Agency, 2008: Model-based analysis and tracking of airborne mercury
 574 emissions to assist in watershed planning. *United States Environmental Protection*
 575 *Agency*, 350 pp.
 576 Foley, G. R., and B. N. Hanstrum, 1994: The Capture of Tropical Cyclones by Cold Fronts off
 577 the West Coast of Australia. *Weather and Forecasting*, **9**, 577-592.
 578 Funk, C., and M. Brown, 2009: Declining global per capita agricultural production and warming
 579 oceans threaten food security. *Food Security*, **1**, 271-289.
 580 Funk, C., M. Dettinger, J. C. Michaelsen, J. P. Verdin, M. E. Brown, M. Barlow, and A. Hoell,
 581 2008: Warming of the Indian Ocean threatens eastern and southern African food security
 582 but could be mitigated by agricultural development. *Proceedings of the National*
 583 *Academy*, **105**, 11081-11086.
 584 Funk, C., G. Senay, A. Asfaw, J. P. Verdin, G. Eilerts, J. C. Michaelsen, S. Amer, and R.
 585 Choularton, 2005: Recent Drought Tendencies in Ethiopia and equatorial-subtropical
 586 eastern Africa. *Vulnerability to Food Insecurity: Factor Identification and*
 587 *Characterization Rep. 01/2005*, 13 pp.
 588 Gierach, M. M., M. A. Bourassa, P. Cunningham, J. J. O'Brien, and P. D. Reasor, 2007:
 589 Vorticity-Based Detection of Tropical Cyclogenesis. *Journal of Applied Meteorology and*
 590 *Climatology*, **46**, 1214-1229.

591 Govaerts, Y. M., A. Lattanzio, M. Taberner, and B. Pinty, 2008: Generating global surface
592 albedo products from multiple geostationary satellites. *Remote Sensing of Environment*,
593 **112**, 2804-2816.

594 Guentzel, J. L., W. M. Landing, G. A. Gill, and C. D. Pollman, 2001: Processes Influencing
595 Rainfall Deposition of Mercury in Florida. *Environmental Science & Technology*, **35**,
596 863-873.

597 Hart, R. E., and J. L. Evans, 2001: A Climatology of the Extratropical Transition of Atlantic
598 Tropical Cyclones. *Journal of Climate*, **14**, 546-564.

599 Hennon, C. C., and J. S. Hobgood, 2003: Forecasting Tropical Cyclogenesis over the Atlantic
600 Basin Using Large-Scale Data. *Monthly Weather Review*, **131**, 2927-2940.

601 Hennon, C. C., C. N. Helms, K. R. Knapp, and A. R. Bowen, 2011: An Objective Algorithm for
602 Detecting and Tracking Tropical Cloud Clusters: Implications for Tropical Cyclogenesis
603 Prediction. *Journal of Atmospheric and Oceanic Technology*, **Submitted**.

604 Holben, B. N., and Coauthors, 1998: AERONET - A federated instrument network and data
605 archive for aerosol characterization. *Remote Sensing of the Environment*, **66**, 1-16.

606 Holmes, C. D., 2008: Mercury deposition to the Gulf Coast region from deep convection and
607 long-range atmospheric transport. *AGU Fall Meeting*, San Francisco, CA, Eos
608 Transactions.

609 ———, 2010: Thunderstorms increase mercury concentration in rainfall, **In preparation**.

610 Janowiak, J. E., R. J. Joyce, and Y. Yarosh, 2001: A real-time global half-hourly pixel-resolution
611 infrared dataset and its applications. *Bulletin of the American Meteorological Society*, **82**,
612 205-217.

613 Jones, S. C., and Coauthors, 2003: The Extratropical Transition of Tropical Cyclones: Forecast
614 Challenges, Current Understanding, and Future Directions. *Weather and Forecasting*, **18**,
615 1052-1092.

616 Joyce, R., J. Janowiak, and G. Huffman, 2001: Latitudinally and Seasonally Dependent Zenith-
617 Angle Corrections for Geostationary Satellite IR Brightness Temperatures. *Journal of*
618 *Applied Meteorology*, **40**, 689-703.

619 Joyce, R. J., J. E. Janowiak, P. A. Arkin, and P. Xie, 2004: CMORPH: A Method that Produces
620 Global Precipitation Estimates from Passive Microwave and Infrared Data at High
621 Spatial and Temporal Resolution. *Journal of Hydrometeorology*, **5**, 487-503.

622 Klein, P. M., P. A. Harr, and R. L. Elsberry, 2000: Extratropical Transition of Western North
623 Pacific Tropical Cyclones: An Overview and Conceptual Model of the Transformation
624 Stage. *Weather and Forecasting*, **15**, 373-395.

625 Knapp, K. R., 2002: Quantification of aerosol signal in GOES-8 visible imagery over the U.S.
626 *Journal of Geophysical Research*, **107**, 10.1029/2001JD002001.

627 ———, 2008a: Scientific data stewardship of International Satellite Cloud Climatology Project B1
628 global geostationary observations. *Journal of Applied Remote Sensing*, **2**, 023548

629 ———, 2008b: Calibration of long-term geostationary infrared observations using HIRS. *Journal*
630 *of Atmospheric and Oceanic Technology*, **25**, 183-195.

631 Knapp, K. R., and J. P. Kossin, 2007: New global tropical cyclone data from ISCCP B1
632 geostationary satellite observations. *Journal of Applied Remote Sensing*, **1**, 013505

633 Knapp, K. R., J. J. Bates, and B. Barkstrom, 2007: Scientific Data Stewardship: Lessons learned
634 from a satellite data rescue effort. *Bulletin of the American Meteorological Society*, **88**,
635 1359-1361.

636 Knapp, K. R., M. C. Kruk, D. H. Levinson, H. J. Diamond, and C. J. Neumann, 2010: The
637 International Best Track Archive for Climate Stewardship (IBTrACS): Centralizing
638 tropical cyclone best track data. *Bulletin of the American Meteorological Society*, **91**,
639 363-376.

640 Kossin, J. P., K. R. Knapp, D. J. Vimont, R. J. Murnane, and B. A. Harper, 2007a: A globally
641 consistent reanalysis of hurricane variability and trends. *Geophysical Research Letters*,
642 **34**, L04815.

643 Kossin, J. P., J. A. Knaff, H. I. Berger, D. C. Herndon, T. A. Cram, C. S. Velden, R. J. Murnane,
644 and J. D. Hawkins, 2007b: Estimating hurricane wind structure in the absence of aircraft
645 reconnaissance. *Weather and Forecasting*, **22**, 89-101.

646 Lee, C. S., 1989: Observational Analysis of Tropical Cyclogenesis in the Western North Pacific.
647 Part I: Structural Evolution of Cloud Clusters. *Journal of Atmospheric Science*, **46**, 2580-
648 2598.

649 Lee, H.-T., A. K. Heidinger, A. Gruber, and R. G. Ellingson, 2004: The HIRS Outgoing
650 Longwave Radiation product from hybrid polar and geosynchronous satellite
651 observations. *Advances in Space Research*, **33**.

652 Lee, H.-T., A. Gruber, R. G. Ellingson, and I. Laszlo, 2007: Development of the HIRS Outgoing
653 Longwave Radiation climate data set. *Journal of Atmospheric and Oceanic Technology*,
654 **24**, 2029-2047.

655 Lindberg, S., and Coauthors, 2007: A Synthesis of Progress and Uncertainties in Attributing the
656 Sources of Mercury in Deposition. *AMBIO: A Journal of the Human Environment*, **36**,
657 19-33.

658 Loew, A., and Y. Govaerts, 2010: Towards Multidecadal Consistent Meteosat Surface Albedo
659 Time Series. *Remote Sensing*, **2**, 957-967.

660 Magnusdottir, G., and C.-C. Wang, 2008: Intertropical Convergence Zones during the Active
661 Season in Daily Data. *Journal of Atmospheric Science*, **65**, 2425-2436.

662 Mercury Deposition Network, 2006: National Atmospheric Deposition Program 2005 Annual
663 Summary. 16 pp.

664 Mergler, D., H. A. Anderson, L. H. M. Chan, K. R. Mahaffey, M. Murray, M. Sakamoto, and A.
665 H. Stern, 2007: Methylmercury Exposure and Health Effects in Humans: A Worldwide
666 Concern. *AMBIO: A Journal of the Human Environment*, **36**, 3-11.

667 National Research Council, 2004: Climate Data Records from Environmental Satellites, 116 pp.

668 Rew, R., and G. Davis, 1990: NetCDF: an interface for scientific data access. *Computer*
669 *Graphics and Applications, IEEE*, **10**, 76-82.

670 Reynolds, R. W., N. A. Rayner, T. M. Smith, D. C. Stokes, and W. Wang, 2002: An Improved In
671 Situ and Satellite SST Analysis for Climate. *Journal of Climate*, **15**, 1609-1625.

672 Schaaf, C. B., and Coauthors, 2002: First operational BRDF, albedo nadir reflectance products
673 from MODIS. *Remote Sensing of Environment*, **83**, 135-148.

674 Scheuhammer, A. M., M. W. Meyer, M. B. Sandheinrich, and M. W. Murray, 2007: Effects of
675 Environmental Methylmercury on the Health of Wild Birds, Mammals, and Fish.
676 *AMBIO: A Journal of the Human Environment*, **36**, 12-19.

677 Schmetz, J., S. A. Tjemkes, M. Gube, and L. van de Berg, 1997: Monitoring deep convection
678 and convective overshooting with METEOSAT. *Advances in Space Research*, **19**, 433-
679 441.

680 Selin, N. E., and D. J. Jacob, 2008: Seasonal and spatial patterns of mercury wet deposition in
681 the United States: Constraints on the contribution from North American anthropogenic
682 sources. *Atmospheric Environment*, **42**, 5193-5204.

683 Sharp, R. J., M. A. Bourassa, and J. J. O'Brien, 2002: Early Detection of Tropical Cyclones
684 Using Seawinds-Derived Vorticity. *Bulletin of the American Meteorological Society*, **83**,
685 879-889.

686 Sinclair, M. R., 2002: Extratropical Transition of Southwest Pacific Tropical Cyclones. Part I:
687 Climatology and Mean Structure Changes. *Monthly Weather Review*, **130**, 590-609.

688 Soden, B. J., and F. P. Bretherton, 1993: Upper Tropospheric Relative Humidity From the GOES
689 6.7 μm Channel: Method and Climatology for July 1987. *J. Geophys. Res.*, **98**, 16669-
690 16688.

691 Soler, T., and D. W. Eisemann, 1994: Determination of look angles to geostationary
692 communication satellites. *J. Surv. Eng. ACSE*, **120**, 115-127.

693 Tian, B. J., B. J. Soden, and X. Q. Wu, 2004: Diurnal cycle of convection, clouds, and water
694 vapor in the tropical upper troposphere: Satellites versus a general circulation model.
695 *Journal of Geophysical Research-Atmospheres*, **109**, D10101.

696 Turk, F. J., and S. D. Miller, 2005: Toward improved characterization of remotely sensed
697 precipitation regimes with MODIS/AMSR-E blended data techniques. *IEEE*
698 *Transactions on Geoscience and Remote Sensing*, **43**, 1059-1069.

699 Waliser, D. E., and C. Gautier, 1993: A Satellite-derived Climatology of the ITCZ. *Journal of*
700 *Climate*, **6**, 2162-2174.

701 Wang, C.-C., and G. Magnusdottir, 2006: The ITCZ in the Central and Eastern Pacific on
702 Synoptic Time Scales. *Monthly Weather Review*, **134**, 1405-1421.

703 Xie, P., and P. A. Arkin, 1997: Global Precipitation: A 17-Year Monthly Analysis Based on
704 Gauge Observations, Satellite Estimates, and Numerical Model Outputs. *Bulletin of the*
705 *American Meteorological Society*, **78**, 2539-2558.

706 Young, D. F., P. Minnis, D. R. Doelling, G. G. Gibson, and T. Wong, 1998: Temporal
707 Interpolation Methods for the Clouds and the Earth's Radiant Energy System (CERES)
708 Experiment. *Journal of Applied Meteorology*, **37**, 572-590.

709 Zender, C. S., 2008: Analysis of self-describing gridded geoscience data with netCDF Operators
710 (NCO). *Environmental Modelling & Software*, **23**, 1338-1342.

711

712

713

Figure Captions

Figure 1 – a) Time series of ISCCP B1 geostationary observational coverage at the Equator (shading limited to a view zenith angle of 60° for illustrative purposes). b-e) Sample GridSat coverage for typical satellite coverages: b) Two-satellite coverage with only GOES-East and -West in 1980, c) Four-satellite coverage that is typical of most of the period from 1982 through 1998, d) typical three-satellite coverage when the U.S. was operating only one satellite (e.g., 1985-1987 or 1989-1992) and e) five-satellite coverage that is typical of the current era (1998 to present).

Figure 2 - Merged GridSat IR image (left) from 1 Jan. 2008 with satellite identification (right). Top row is the nadir-most observations, followed by the second-most and third-most nadir observations (second and third rows, respectively). The satellites FY-2C, GOES-11, GOES-12, Meteosat-7, Meteosat-9, MTSAT-1R are color-coded as red, orange, yellow, green, blue, and violet.

Figure 3 – Cloud cluster track frequency (clusters per year within 55km of any point) for the first decade of global satellite coverage (1998-2007). Contour levels are set at 1, 5 and 10 per year.

Figure 4 - HURSAT image of 1992 Hurricane Andrew from August 23, 1992 along with a time series of its maximum sustained wind (in knots).

Figure 5 - Example of ITCZ detection in the east Pacific using the statistical model for 18 August 2000 at 2100 UTC. Shading represents IR temperature from GridSat, the black line outlines the identified location of the ITCZ. The North American coastline is outlined in white.

Figure 6 - (A) Mercury wet deposition in the eastern United States for 2005. Stars show sites analyzed here. (B) Mercury wet deposition for summers 2001-2006 and mean infrared (IR) cloud temperature from GridSat IR. See text for IR temperature averaging method. (C) Mercury wet

deposition and precipitation for three different cloud temperature ranges. Lines show mean concentration in 50 mm precipitation bins for the coldest (temperature < 240K) and warmest (temperature > 260K) clouds. [Figure adapted from (Holmes 2008, 2010) with deposition map adapted from (Mercury Deposition Network 2006)]

Figure 7 – July-September (JJAS) air temperature and rainfall estimates based on combinations of GridSat infrared fields and in situ station observations. The top two panels show decadal average air temperature (left) and rainfall (right) for the 1999-2008 period. The bottom panels show the differences between these decadal averages and the 1984-1993 average (the 1999-2008 average minus the 1984-1993 average).

Figure 8 - Comparison of diurnal OLR models from the HIRS climatology and GridSat for August 2002. The GridSat OLR helps to verify the representativeness of the climatological OLR diurnal models used in the production of the HIRS OLR climate data record. The arrows in the central panel indicate the phases of the OLR diurnal models with the 12 o'clock local time pointing north, running counter-clockwise. The surrounding plots compare the diurnal models for selected regions with distinctively different types of diurnal variations. The mean values of GridSat OLR in each diurnal plot were adjusted to those of the HIRS to aid visual comparison.

754

755 **Tables**

756 Table 1 - Summary of similarities and differences between the CPC-4km product and the

757 GridSat dataset.

	CPC-4km	GridSat
Spatial resolution	4km	8km
Temporal resolution	30 min	180 min
Channels	1 (IR)	3 (IR, WVP, visible)
Monthly Volume (<i>uncompressed</i>)	45 GB	40 GB
Period of record	2000-present	1980-present
Intersatellite normalization	Yes	Yes
Temporal normalization	No	Yes
Format	Unformatted binary	netCDF

758

Figures

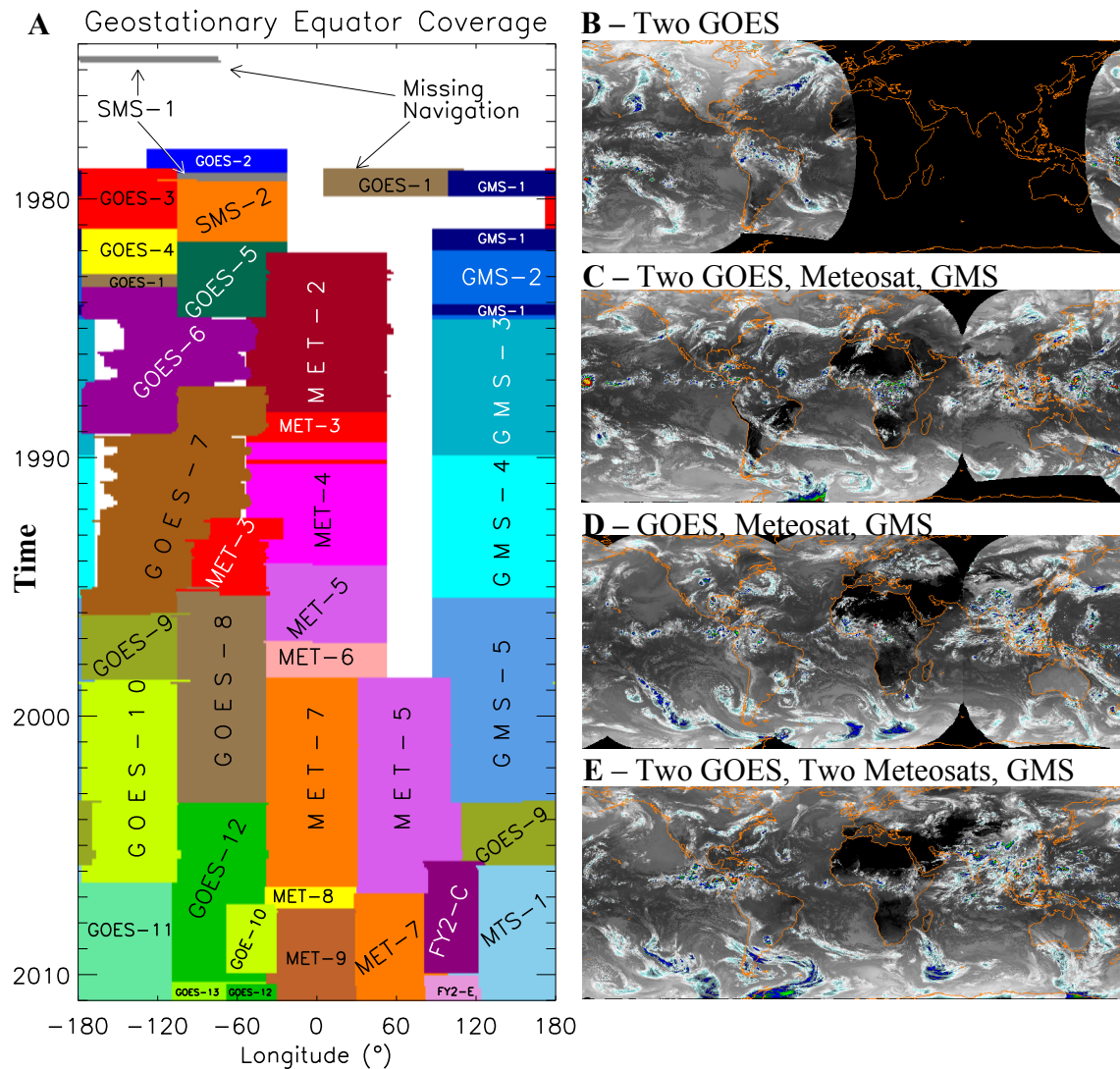
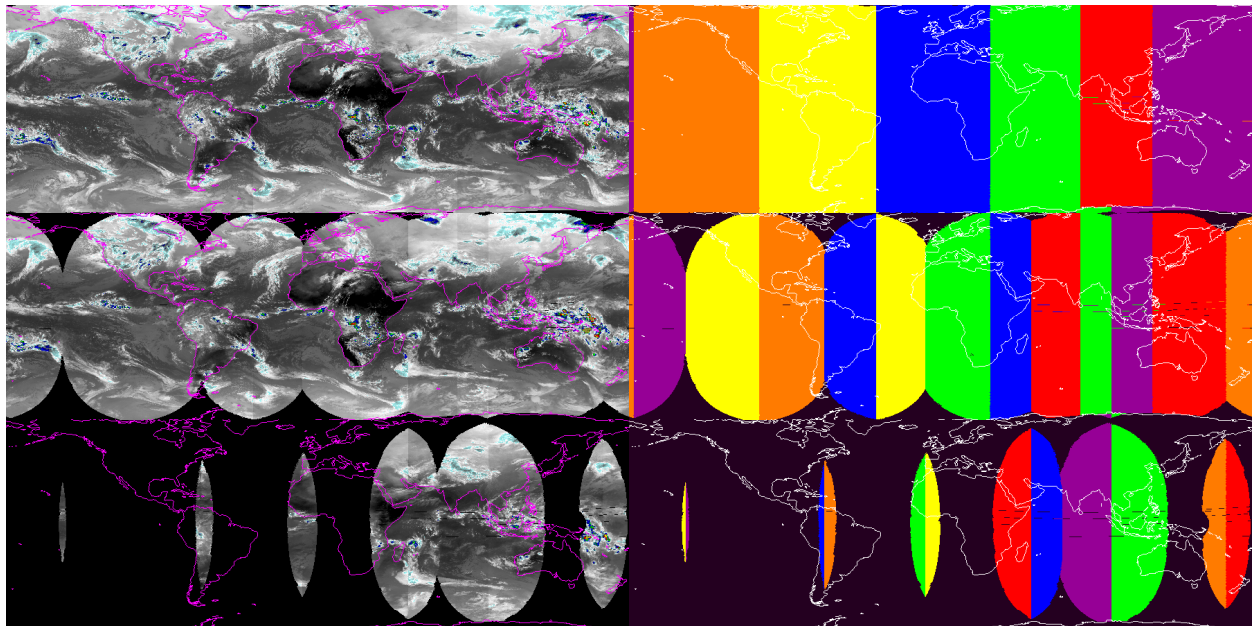


Figure 1 – a) Time series of ISCCP B1 geostationary observational coverage at the Equator (shading limited to a view zenith angle of 60° for illustrative purposes). b-e) Sample GridSat coverage for typical satellite coverages: b) Two-satellite coverage with only GOES-East and -West in 1980, c) Four-satellite coverage that is typical of most of the period from 1982 through 1998, d) typical three-satellite coverage when the U.S. was operating only one satellite (e.g., 1985-1987 or 1989-1992) and e) five-satellite coverage that is typical of the current era (1998 to present).

768



769

770 Figure 2 - Merged GridSat IR image (left) from 1 Jan. 2008 with satellite identification (right).

771 Top row is the nadir-most observations, followed by the second-most and third-most nadir

772 observations (second and third rows, respectively). The satellites FY-2C, GOES-11, GOES-12,

773 Meteosat-7, Meteosat-9, MTSAT-1R are color-coded as red, orange, yellow, green, blue, and

774 violet. Black regions denote missing data.

775 SWF/GIF

776 Animation location:

777 ftp://eclipse.ncdc.noaa.gov/pub/misc/kknapp/bams_grisat/GriSat-Construction.gif or

778 ftp://eclipse.ncdc.noaa.gov/pub/misc/kknapp/bams_grisat/GridSat-Construction.swf

779

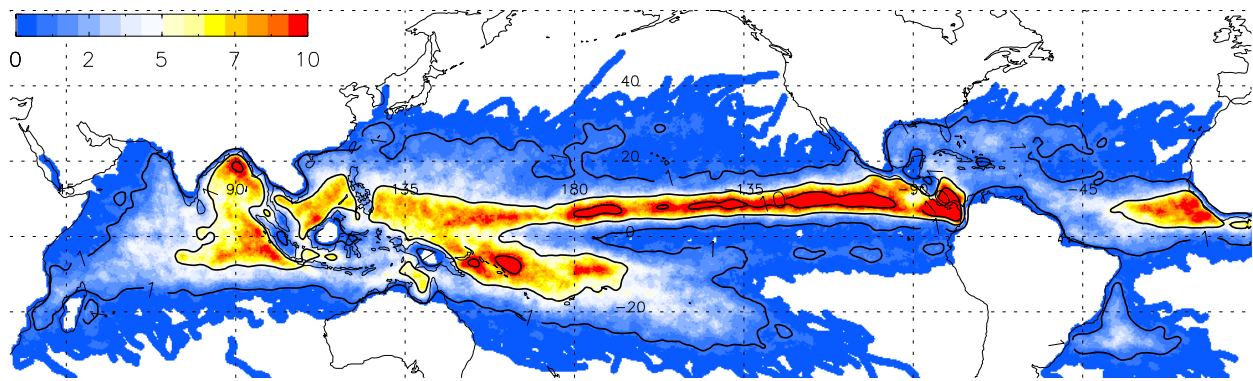
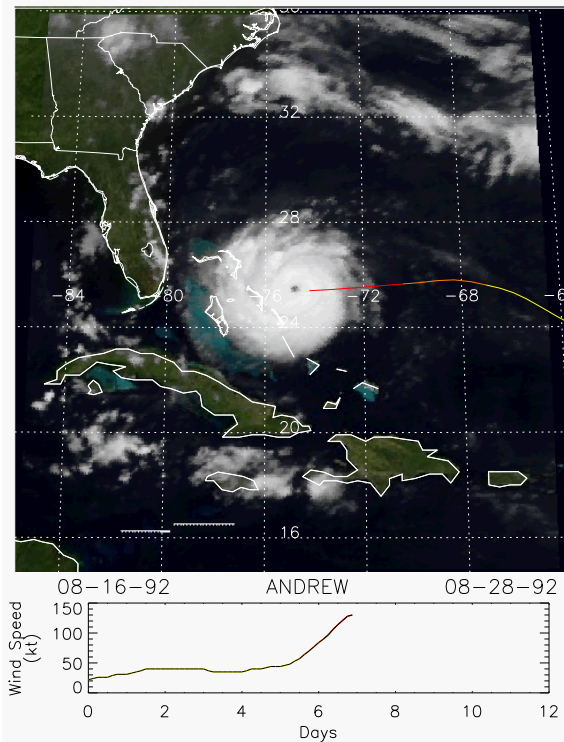


Figure 3 – Cloud cluster track frequency (clusters per year within 55km of any point) for the first decade of global satellite coverage (1998-2007). Contour levels are set at 1, 5 and 10 per year.

Clusters over land and those that formed north of 30 degrees latitude were filtered out.

788



789

790 Figure 4 - HURSAT image of 1992 Hurricane Andrew from August 23, 1992 along with a time
791 series of its maximum sustained wind (in knots).

792 MPEG/GIF/SWF

793 Animation location

794 <ftp://eclipse.ncdc.noaa.gov/pub/hursat/b1/v03/mpg/1992230NA11325-AND.mpg>

795 (right click link and "Save as..." then open using Windows Media Player, a codec may be
796 required)

797 ftp://eclipse.ncdc.noaa.gov/pub/misc/kknapp/bams_grisat/andrew.gif or

798 ftp://eclipse.ncdc.noaa.gov/pub/misc/kknapp/bams_grisat/andrew.swf

799

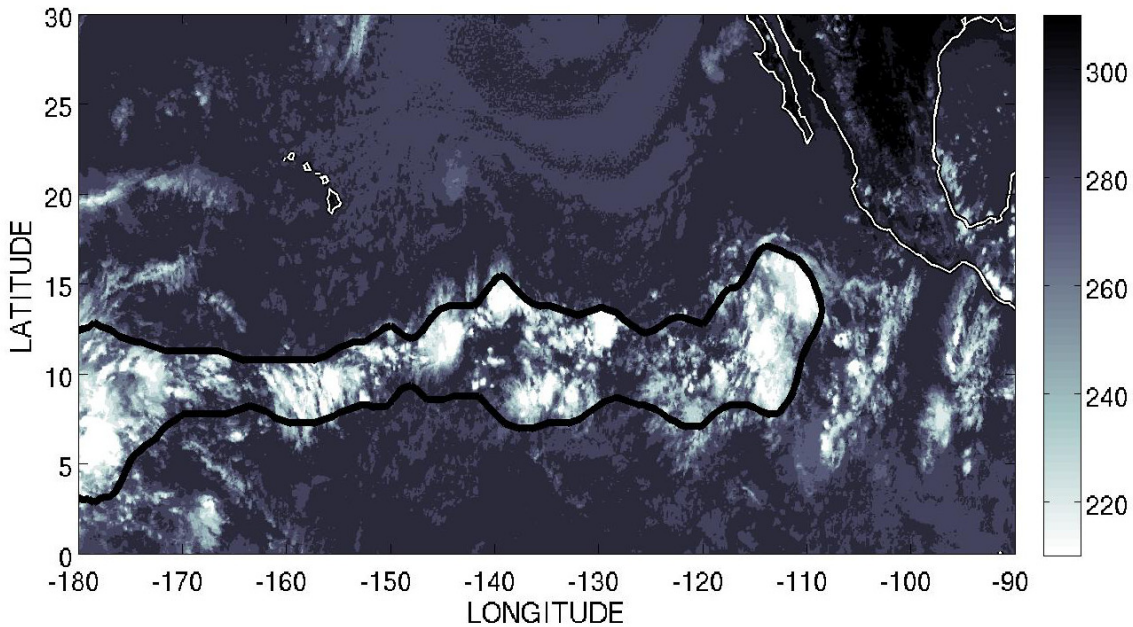


Figure 5 - Example of ITCZ detection in the east Pacific using the statistical model for 18 August 2000 at 2100 UTC. Shading represents IR temperature from GridSat, the black line outlines the identified location of the ITCZ. The North American coastline is outlined in white.

GIF/SWF

Animation location:

ftp://ftp.ncdc.noaa.gov/pub/data/papers/bams_grisat/IRloop.gif or

ftp://eclipse.ncdc.noaa.gov/pub/misc/kknapp/bams_grisat/IRloop.gif or

ftp://eclipse.ncdc.noaa.gov/pub/misc/kknapp/bams_grisat/IRloop.swf

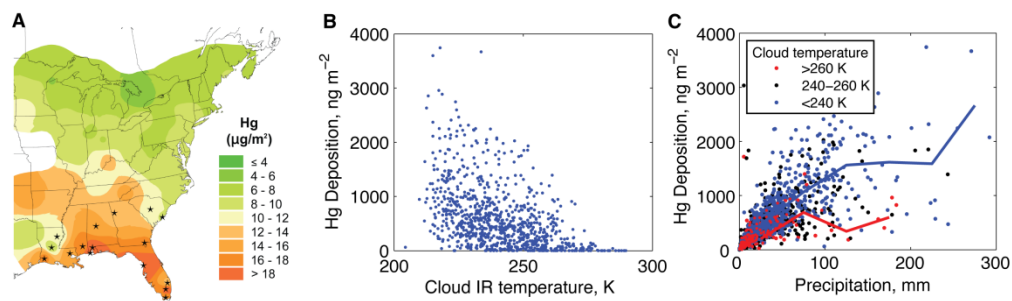


Figure 6 - (A) Mercury wet deposition in the eastern United States for 2005. Stars show sites analyzed here. (B) Mercury wet deposition for summers 2001-2006 and mean infrared (IR) cloud temperature from GridSat IR. See text for IR temperature averaging method. (C) Mercury wet deposition and precipitation for three different cloud temperature ranges. Lines show mean concentration in 50 mm precipitation bins for the coldest (temperature < 240K) and warmest (temperature > 260K) clouds. [Figure adapted from (Holmes 2008, 2010) with deposition map adapted from (Mercury Deposition Network 2006)]

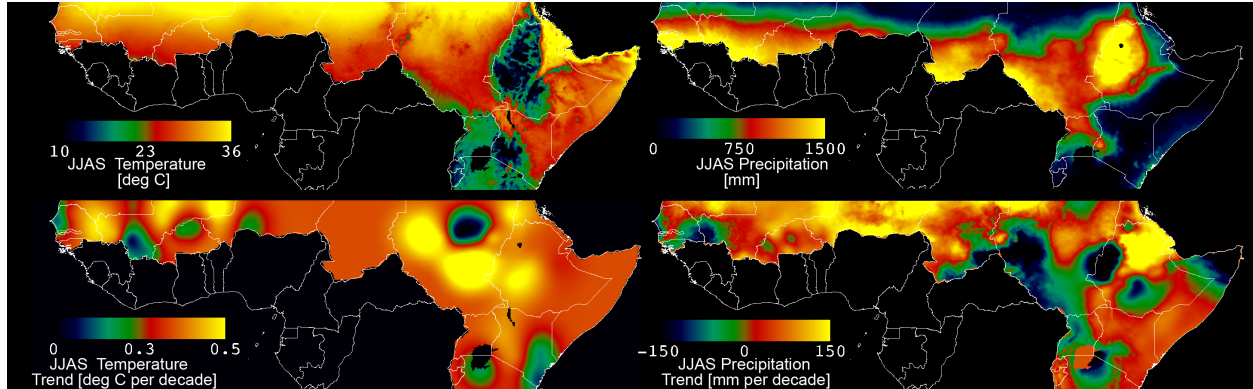


Figure 7 – July-September (JJAS) air temperature and rainfall estimates based on combinations of GridSat infrared fields and in situ station observations. The top two panels show decadal average air temperature (left) and rainfall (right) for the 1999-2008 period. The bottom panels show the differences between these decadal averages and the 1984-1993 average (the 1999-2008 average minus the 1984-1993 average).

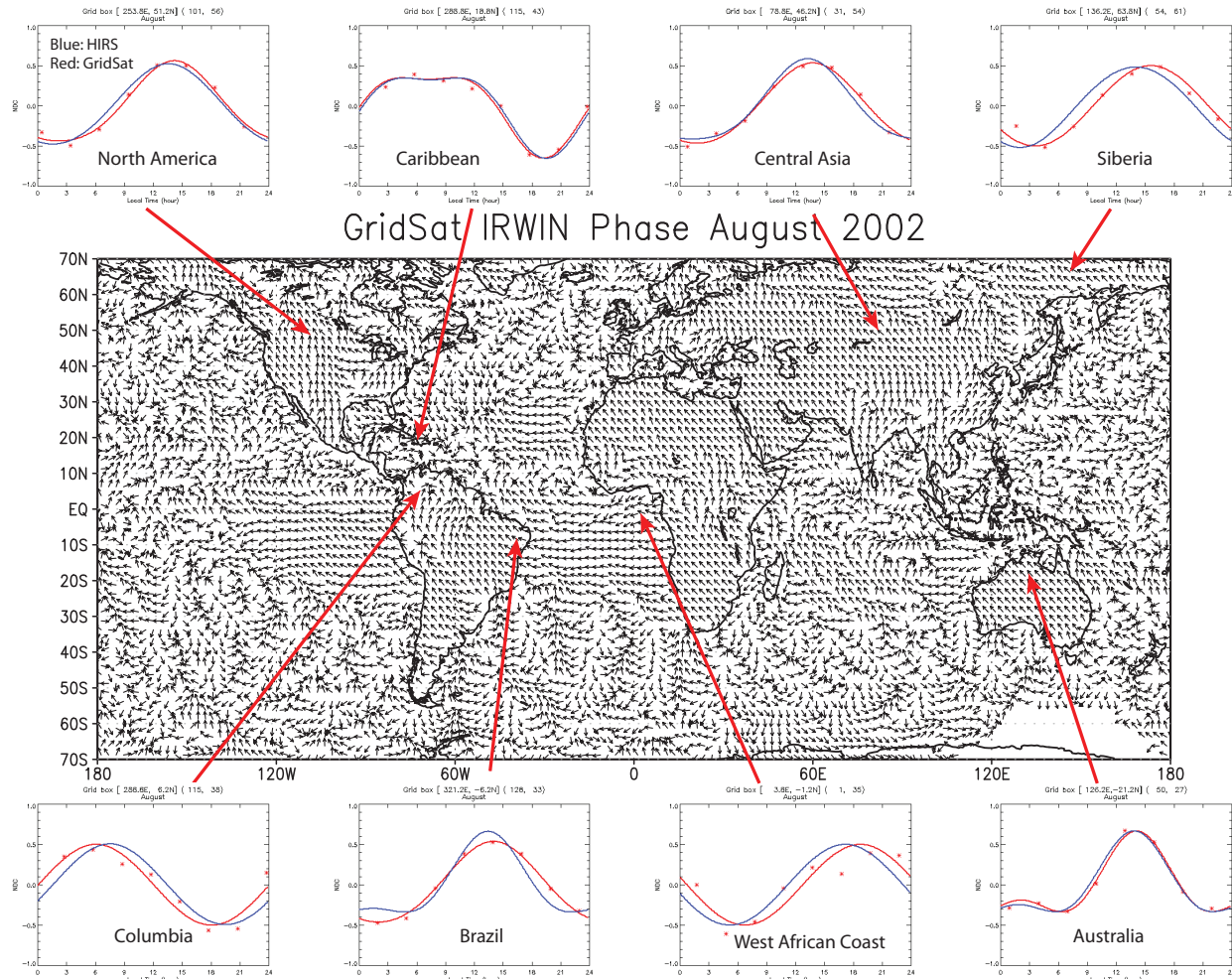


Figure 8 - Comparison of diurnal OLR models from the HIRS climatology and GridSat for August 2002. The GridSat OLR helps to verify the representativeness of the climatological OLR diurnal models used in the production of the HIRS OLR climate data record. The arrows in the central panel indicate the phases of the OLR diurnal models with the 12 o'clock local time pointing north, running counter-clockwise. The surrounding plots compare the diurnal models for selected regions with distinctively different types of diurnal variations. The mean values of GridSat OLR in each diurnal plot were adjusted to those of the HIRS to aid visual comparison.

842

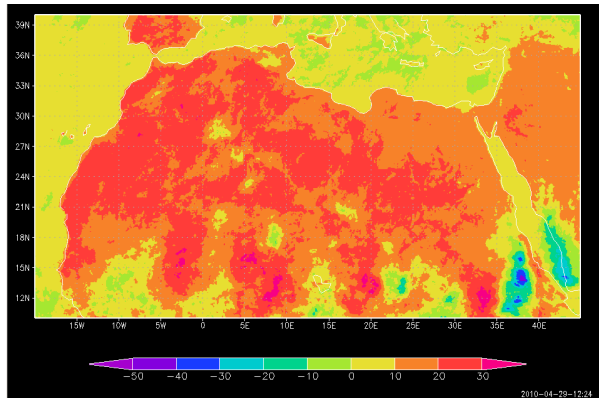
```
#!/bin/bash

for hour in 00 03 06 09 12 15 18 21
do
    ncra GRIDSAT-B1.2002.07.??.$hour.nc \
        -d lat,10.,40. -d lon,-20.,45. -v irwin \
        -o GRIDSAT-B1.2002.07.$hour.nc
done
ncrcat GRIDSAT-B1.2002.07.???.nc -o GRIDSAT-B1.2002.07.nc
```

843

844 Figure SB1 – BASH code that uses netCDF operators to process one month of GridSat data of
845 the Sahara Desert into diurnally-averaged brightness temperatures.

846



847

848 Figure SB2 – Average daily temperature change (K) between 3 UTC and 15 UTC over the

849 Saharan desert for August 2002.

Globally Gridded Satellite (GridSat) Observations for Climate Studies

Kenneth R. Knapp¹, Steve Ansari¹, Caroline Bain², Mark A. Bourassa³, Michael J. Dickinson⁴, Chris Funk⁵, Chip N. Helms⁶, Christopher C. Hennon⁷, Christopher D. Holmes⁸, George J. Huffman⁹, James P. Kossin¹, Hai-Tien Lee¹⁰, Alexander Loew¹¹, Gudrun Magnúsdóttir¹²

- 1 NOAA National Climatic Data Center
- 2 Univ. of California at Irvine (now at Met Office, Exeter, Devon, UK)
- 3 Florida State Univ.
- 4 Dept. of Earth and Atmospheric Sciences, The Univ. at Albany/SUNY (now at WeatherPredict Consulting, Wakefield, RI)
- 5 USGS Center for Earth Resource Observations and Science
- 6 Univ. of North Carolina Asheville (now at Florida State Univ.)
- 7 Univ. of North Carolina Asheville
- 8 Dept. of Earth and Planetary Science, Harvard Univ.
- 9 Science Systems and Applications, Inc. and NASA Goddard Space Flight Center
- 10 Cooperative Institute for Climate Studies, Univ. of Maryland, College Park
- 11 Max-Planck-Institute for Meteorology, KlimaCampus, Hamburg, Germany
- 12 Univ. of California at Irvine

To be submitted to the *Bulletin of the American Meteorological Society*

Geostationary satellites, each of which continually observes the same part of the Earth, have provided routine, fine-scale Earth observations since the 1970s. Despite the long period of record, use of these data in climate studies has proved to be difficult. Historically, each satellite operator has maintained an independent archive center. In part, this has been true because the full-resolution data are quite voluminous, even by modern standards. Another issue is that the data have been stored using diverse formats that vary between centers, and even within each center. Taken together, these issues have effectively prevented the uniform processing needed for long-term multi-satellite climate studies. The International Satellite Cloud Climatology Project set the stage for overcoming these issues by archiving a subset of the full resolution geostationary data at ~10 km resolution at 3 hourly intervals beginning in 1983. This intermediate archive overcame the first two issues, but not the third. Starting about five years ago, the NOAA National Climatic Data Center undertook the task of providing convenient access to these data by remapping the data to a standard map projection, recalibrating the data to optimize homogeneity over time, correcting for biases due to varying zenith view angles, and reformatting the data for broad public distribution. As a bonus, they incorporated additional geosynchronous data that extend the record back to 1980. The resulting Gridded Satellite (GridSat) dataset provides observations recorded by three different sensor channels. Two of these channels have been used on the geosynchronous satellites from the beginning of the record, and the third came into general use in the 1990s. A final design issue is that the satellites usually have some overlapping coverage in space at each time. While some users simply want a “best” global map, others want to see the complete data coverage for a particular satellite. We developed an innovative data layering approach that provides the single global map at each time, allows access to complete satellite data, and minimizes wasted storage space. The GridSat data

are already in use by the meteorological community. Examples include reanalysis of tropical cyclones, studies of global precipitation, and detection and tracking of the Intertropical Convergence Zone.